

Kinematics of AGN Jets

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Abstract. The fine-scale structure and the kinematics of relativistic active galactic nuclei (AGN) jets have been studied by very-long-baseline interferometry at very high resolutions since 1998 at 2 cm wavelength for a sample of over a hundred radio sources (VLBA 2cm Survey and MOJAVE programs). Since 2007, this is being complemented by the TANAMI project, based on southern observations with the Australian LBA at 3.6 cm and 1.1 cm wavelengths. From our observation campaign, we find that most of the radio jets show linear morphologies at parsec-scales, but some of show curvature and non-radial motions. Features are observed to move at highly relativistic speeds, with Lorentz factors extending above values of 30. We also provide a brief description of the relationship of our radio findings with the AGN observations by the new *Fermi Gamma-ray Space Telescope*.

1. Introduction

Through the combination of radio telescopes spread world wide, Very-Long-Baseline Interferometry (VLBI) yields the highest resolutions and the most accurate positions in astronomy. At a wavelength of 2 cm, i.e., the Very Long Baseline Array (VLBA) provides resolutions of the order of 1 milliarcsecond (mas) (that is, of parsec scales for quasars and BL Lac objects at moderate redshifts, and far below this for the closer radio galaxies). VLBI has a large sensitivity when using large telescopes, but is in general limited to high brightness temperature sources (above 10^6 K) and to narrow fields (not larger than the arc second, generally limited by the correlator parameters rather than by the beam size of the single telescopes involved in the observations), making the source structure to be easily resolved out. It is, thus, an invaluable technique to study the highly relativistic jets AGN.

Due to relativistic effects, the intrinsic quantities in the AGN have to be deduced from the observed ones, which are affected by Doppler boosting and light travel time effects. Table 1 provides the basic relationships between the measured and the observed quantities. As a result of Doppler boosting, most of the AGN jets appear one-sided. Some close galaxies with small Doppler factors show jet and counter-jet with more symmetric features.

Prior to the VLBA construction in the early 1990s, monitoring programs of AGN were difficult due to the sparse number of available antennas, the limited resources in terms of telescope time and recording media, and the difficulties to schedule repeated, homogeneous observations. In 1994 we initiated a VLBA programme at 15 GHz: the 2 cm VLBA Survey¹ (see Table 2). The aim of the programme is to study the parsec-scale structure and kinematics of relativistic AGN jets to understand the acceleration and collimation of relativistic jets. The program was continued

¹ See <http://www.nrao.edu/2cmsurvey/>.

Table 1. Basic jet properties and radio/VLBI measurements

Basic jet properties		What we observe	
Jet Plasma Bulk Velocity	$\beta = v/c^{(a)}$	Apparent Speed	$\beta_{\text{app}} = \beta \sin \theta / (1 - \beta \cos \theta)^{(b)}$
Intrinsic Luminosity	L_{int}	Luminosity	$L_{\text{obs}} = L_{\text{int}} \times \delta^{n(c)}$
Intrinsic Brightness Temperature	$T_{\text{b,int}}$	Brightness Temperature	$T_{\text{b,obs}} = T_{\text{b,int}} \times \delta$
Bulk Lorentz Factor	$\Gamma = (1 - \beta^2)^{-1/2}$	Doppler Beaming	$\delta = \Gamma^{-1} (1 - \beta \cos \theta)^{-1}$

^a v is the speed of the plasma, and c is the light speed.

^b θ is the viewing angle, notice that $\beta_{\text{app,max}} \approx \Gamma$ when $\theta = \Gamma^{-1}$.

^c n depends on the jet geometry and is typically in the range between 2 and 3.

as MOJAVE² since 2003. This effort, limited to declinations over -20° , is complemented since 2007 by the TANAMI³ program for the Southern skies ($\delta < -30^\circ$). The nominal resolutions of the images are slightly below 1 mas, and with typical overall on-source observing times of 1 hr, dynamic ranges up to 1000:1 are achieved. To monitor the jets in the radio sources, the feature positions and sizes of the radio images in the sky are measured directly, or alternatively, models are applied to the interferometric visibility data. After several observations, their time evolution is studied.

Our effort in this field is complementary with further kinematic surveys performed at longer wavelengths (e.g., at $\lambda 3.6$ cm with a global array by Piner *et al* (2007) and at $\lambda 6$ cm on the Caltech-Jodrell Flat Spectrum sample by and Britzen *et al* 2008 and references therein) and shorter ones ($\lambda 7$ mm monitoring on a smaller sample by Jorstad *et al* (2001; 2005)).

2. Observations and selected results

2.1. Overall findings

By collecting subsequent observations of the quasars, the changing positions of the jet features are measured, yielding apparent speed values far beyond 10–15 c . The same measurements in radio galaxies and BL Lac objects show usually lower values. Detailed results for all the sources in the surveys are presented in Kellermann *et al* (2004), E Ros *et al* (in prep.) and M L Lister *et al* (in prep.). Additional images, movies, and preliminary results can also be found on the MOJAVE web site.

2.2. Selected images and jet motions

In Figs. 1–3 we show selected contour images of some sources of our programme. Those are chosen because of their prominent jets and very complex structure. The quasars 3C 279 and 3C 273 have being sampled very intensively in our programme, and for our analysis we also could include a big amount of archival data, since they are used regularly as calibrators and fringe finders at the VLBA. The nearby radio galaxies 3C 111 and NGC 1052 are two cases of sources where we have performed a detailed individual source analysis. In the first one we found trailing components after the ejection of a major feature in the jet (Kadler *et al* 2008), and for the second, a twin jet is seen with mildly relativistic speed of 0.26 c traveling downstream in both sides (see Ros & Kadler, these proceedings, and references therein). The detailed kinematic

² Monitoring Of Jets in Active galactic nuclei with VLBA Experiments, see <http://www.physics.purdue.edu/MOJAVE/>.

³ Tracking Active Galactic Nuclei with the Australian South-African Milliarcsecond Interferometry, <http://http://pulsar.sternwarte.uni-erlangen.de/tanami/>.

Table 2. Our VLBI Monitoring Programs

Name	Time	Refs.	Description
2 cm Survey	1994–2002	1,2,3,4	Over 200 sources imaged regularly with the VLBA at 15 GHz
MOJAVE-I	2002–2006	5,6,7,8	Full linear polarisation added, source list revised to include a flux-limited sample of 135 sources. The selection criteria are: $\delta > -20^\circ$, $ b > 2.5^\circ$, $S_{\text{VLBA}, 15 \text{ GHz}, 1994.0-2003.0} > 1.5 \text{ Jy}$ (2 Jy for $\delta < 0^\circ$).
MOJAVE-II	2006–2007	9	Expanded to 192 jets (58 EGRET blazars with $\delta > -20^\circ$, 33 low-luminosity AGN ($< 10^{26} \text{ W Hz}^{-1}$ at 15 GHz), and 11 jets from the 2 cm Survey with unusual kinematics, including a single epoch on every source at 8.1/8.4/12.1/15.3 GHz during 2006
MOJAVE-III	2008–	9	It will include up to 100 additional <i>FGST</i> -detected sources (see text).
TANAMI	2007–	10	Monitoring of 40 sources at the Southern hemisphere at 0.3 (0.9)-mas resolution at λ 1.1 (3.6) cm. To be expanded to ~ 120 sources in 2008–09. Sources below $\delta = -30^\circ$, selected based on EGRET and on radio flux density and luminosity.

1: Kellermann *et al* (1994); 2: Zensus *et al* (2002), 3: Kellermann *et al* (2004); 4: Kovalev *et al* (2005)
5: Lister and Homan (2005), 6: Homan and Lister (2006), 7: Cooper *et al* (2007), 8: Cara and Lister (2008)
9: M L Lister *et al* (in prep.), 10: Kadler *et al* (2007)

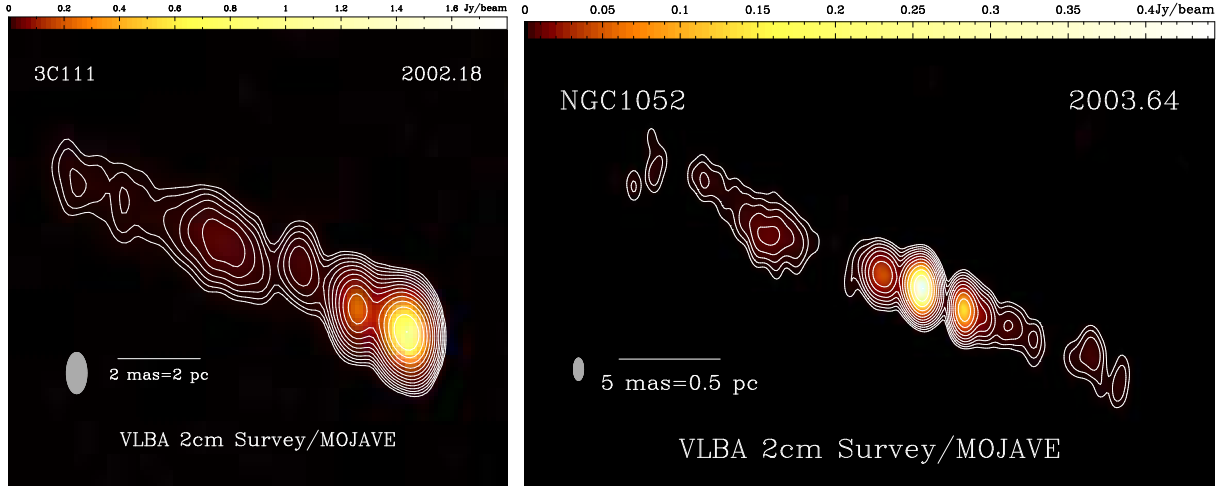


Figure 1. VLBA images of selected sources from the 2 cm/MOJAVE observing programme. The *left* panel shows an image of the Seyfert Galaxy 3C 111 (4C +37.12, B0415+379, J0418+3801, with a redshift $z=0.0485$), where trailing features after the ejection of a major one have been reported; see Kadler *et al* 2008). The *right* panel shows an image of the twin jet in the nearby Seyfert 2 galaxy NGC 1052 (B0238–084, J0241–0815, $z=0.004930$). More details on this source are given in Ros & Kadler (these proceedings).

results of these sources will be presented in M L Lister *et al* (in preparation). We show in more detail results for two sources not belonging to the complete MOJAVE-I sample, for which we have measured kinematics. These sources have high redshifts and the measured motions are slow (not at the abovementioned superluminal ranges over $10c$).

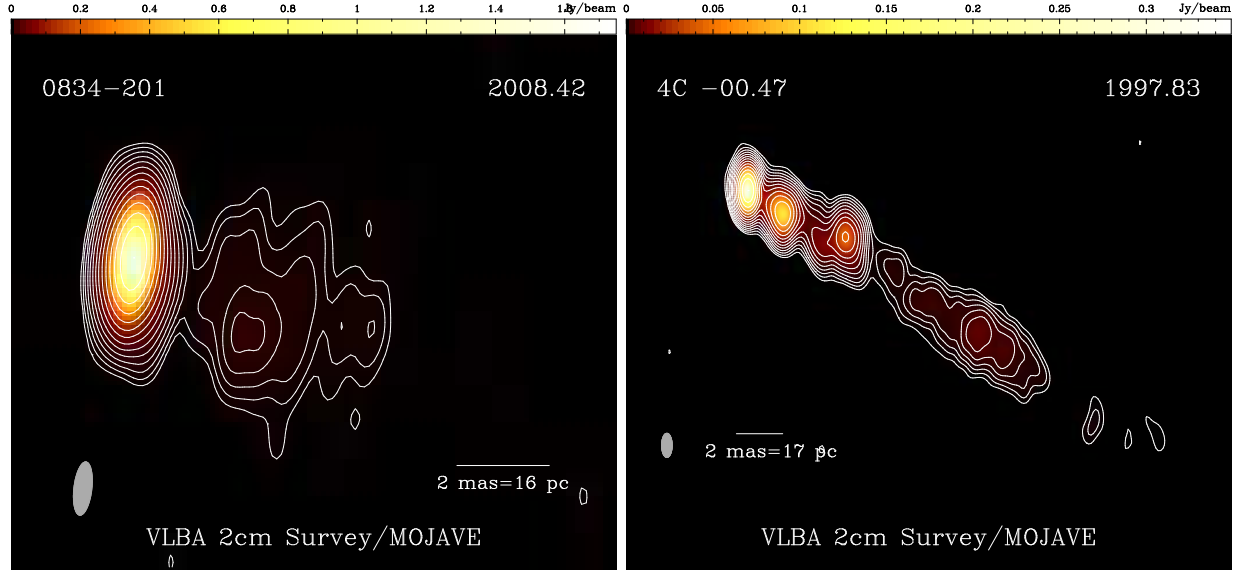


Figure 2. VLBA images of selected sources from the 2 cm/MOJAVE observing programme. The *left* panel shows the high-redshift quasar J0836–2016. In contrast with the 8.4 GHz image published in Ojha *et al* (2004), this source shows emission to the West in a core-jet morphology. Proper motions of the main features are shown in Fig. 4. The *right* panel shows the quasar 4C –00.47, where a more prominent jet towards the south west. Our monitoring program do not show relevant superluminal motions in its components (see Fig. 5).

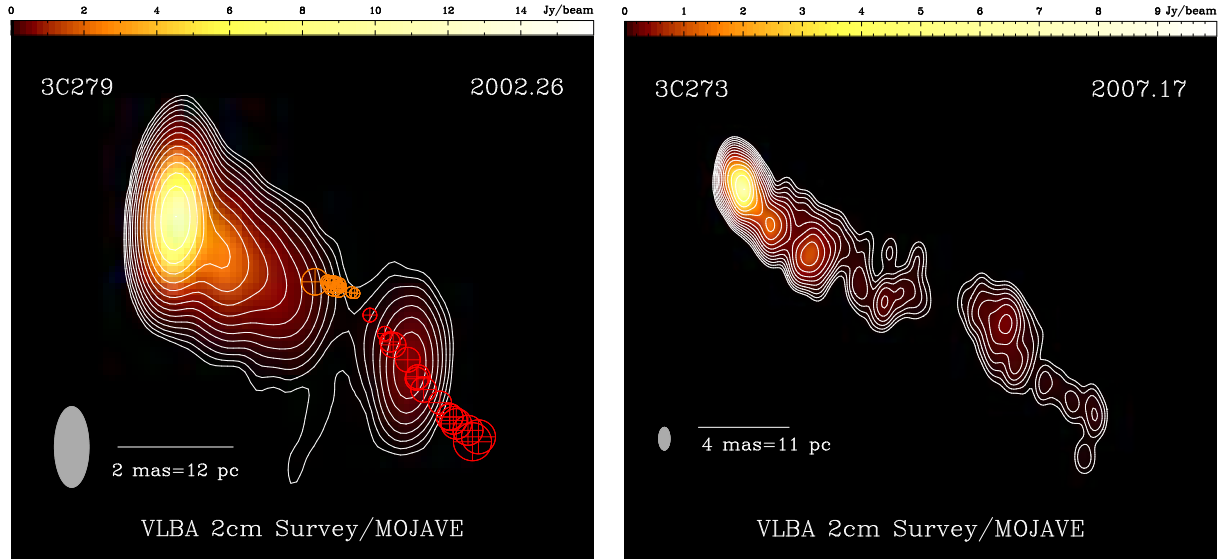


Figure 3. VLBA images of selected sources from the 2 cm/MOJAVE observing programme. The *left* panel shows the jet in 3C 279 (4C –05.55, B1253–4055, J1256–047, with a redshift $z=0.536$). Homan *et al* (2003) reported on the realignment on kiloparsec (kpc) scales of the jet in 3C 279 as observed in milliarcsecond scales (de-projected kpc distance at a very small viewing angle) by a change in direction and speed of a prominent feature. The overlapped red, circled crosses show the positions for this component. The *right* panel shows the jet in the well-known QSO 3C 273 (B1226+023, J1229+0203, 4C +02.32, with a redshift of $z=0.158$).

2.2.1. J0836–2016 This high redshift ($z=2.752$) QSO (OJ–257.5, B0834–201) shows a compact core-jet structure (see Fig. 2) with no big changes between epochs. Preliminary kinematic results are shown in Fig. 4.

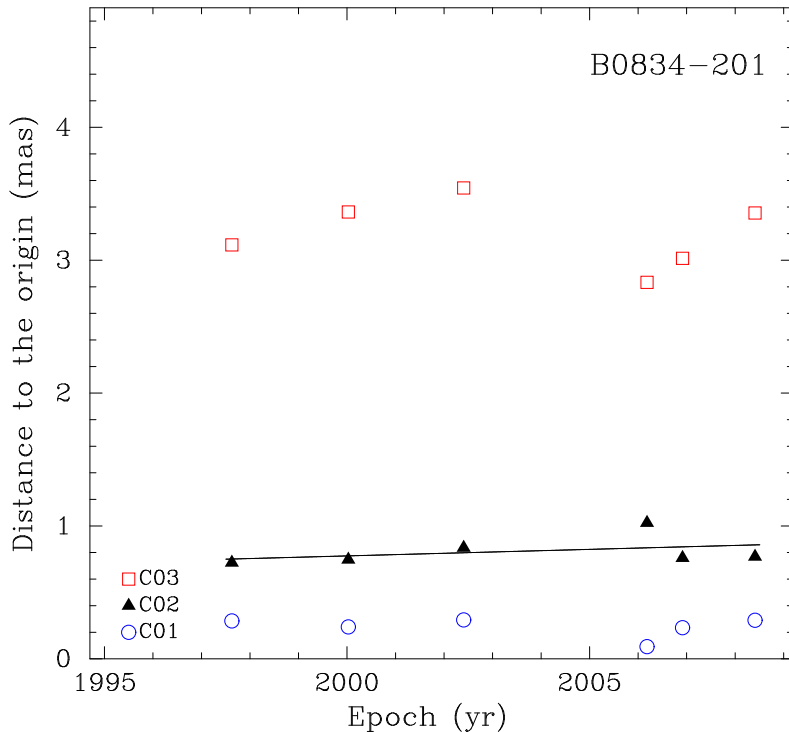


Figure 4. Proper motions in the jet of B0834–201. The points represent the distance of the model fitted features with respect to the base of the jet (core). A linear fit to the distance of component C02 is shown. This component can be taken as stationary, since the fit gives a proper motion of $10 \pm 12 \mu\text{as yr}^{-1}$ (corresponding to $\beta_{\text{app}} = 1 \pm 1$).

2.2.2. 4C–00.47 This QSO (OM–080, B1148–001, J1150–0024, at a redshift of $z=1.975$, presents an extended jet to the Southwest (see Fig. 2). Its imaging is relatively challenging due to its proximity to the equator, what makes a (u, v) -coverage dominated by non-crossing east-west traces. However, our images yield the quality to trace components among different observing epochs. Its jet does not show high speeds, and the kinematical results are compatible with stationary components (see Fig. 5).

3. Kinematics and *FGST*

The *Fermi Gamma-ray Space Telescope* (*FGST*, earlier known as *GLAST*), launched in June 2008, is going to provide an all-sky γ -ray coverage every few hours. Following the discoveries of EGRET, the gamma-ray-sky will be dominated by relativistically-beamed AGN (blazars). Since the bulk of γ -ray emission is expected to be produced close to the jet base, our high-resolution observations are crucial to understand the mechanisms in the jet production and the overall physical properties of the jets, complementing the *FGST* results. The first data of *FGST* are being processed, and new avenues are open for the multi-band studies of AGN by combining VLBI, *FGST* in the γ -ray regime, and *Swift* at intermediate bands in coordinated observations.

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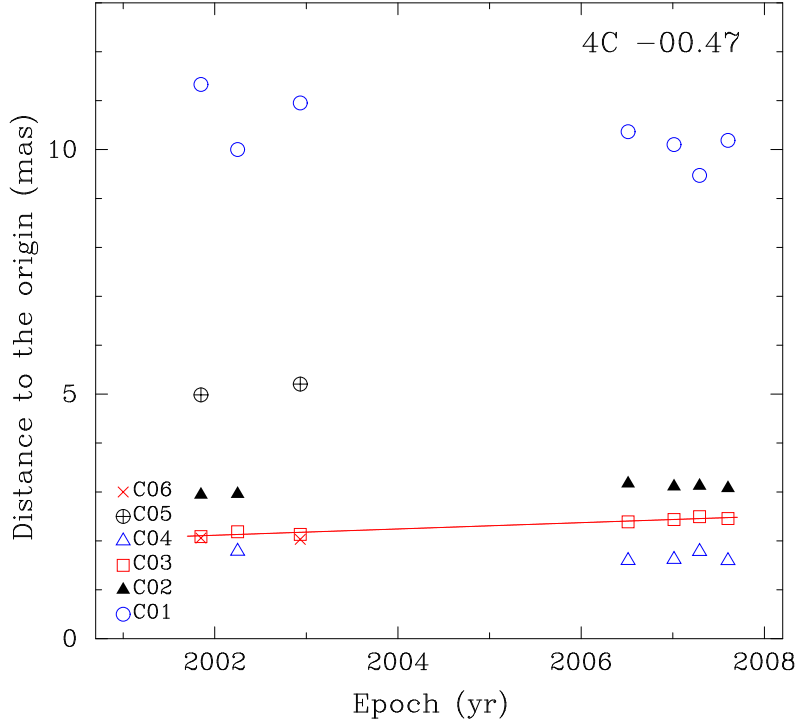


Figure 5. Proper motions in the jet of the quasar 4C –00.47. The relative distance to the innermost feature (core) is shown as a function of time. We have fitted a linear speed to the positions of feature C03, which provides a sky motion of $64 \pm 6 \mu\text{as yr}^{-1}$, which corresponds to $\beta_{\text{app}} = 5.2 \pm 0.5$ and a nominal ejection epoch value of year 1969 ± 3 .

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